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13. ABSTRACT (Maximum 200 words)

This report summarizes our accomplishments during the most recent period of support under this grant. Our research covers several interrelated areas: (a) statistical modeling methods for complex phenomena using multiresolution, hierarchical, and relational structures; (b) sensor fusion for complex space-time phenomena and activities; (c) development of statistical models for shapes and their use in robust methods for shape estimation and recognition; and (d) methods for blending physics and statistical learning in image reconstruction, feature extraction, and fusion. Our research blends methods from several fields—statistics and probability, signal and image processing, mathematical physics, scientific computing, statistical learning theory, and differential geometry—to produce new approaches to emerging and challenging problems in signal and image processing, and each aspect of our program contains both fundamental research in mathematical sciences *and* important applications of direct relevance to Air Force missions. In particular, our research is relevant to automatic target recognition based on synthetic aperture radar and laser radar imagery; wide-area surveillance and information preparation of the battlefield; global awareness and higher-level fusion for situational assessment; and fusion of multiple heterogeneous sensors. In all of these areas we have contacts and interactions with AFRL staff and with industry involved in Air Force programs.

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Final Technical Report for
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MULTIRESOLUTION, GEOMETRIC, AND LEARNING METHODS IN STATISTICAL IMAGE PROCESSING, OBJECT RECOGNITION, AND SENSOR FUSION

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I. Summary: Objectives and Status of Effort

In this report we summarize our accomplishments under the research program supported by Grant F49620-00-1-0362. The basic scope of this research program is to carry out fundamental research in several interrelated areas: (a) the development of methods for the statistical modeling of complex phenomena using multiresolution, hierarchical, and relational structures; (b) the investigation of sensor fusion algorithms for very complex space-time phenomena and activities, especially exploiting the types of structures developed in the first research area; (c) the development of statistical models for shapes and their use in developing robust and statistically optimal methods of shape estimation and recognition; and (d) the investigation of methods for blending physics and methods of statistical learning in order to devise new algorithms for image reconstruction, feature extraction, and fusion.

Key features of this effort are that (i) it blends together methods from several fields--statistics and probabilistic modeling, signal and image processing, mathematical physics, scientific computing, Bayesian networks, statistical learning theory, and differential geometry--to produce new approaches to emerging and challenging problems in signal and image processing; (ii) it both builds on the research results we have obtained under our current grant and also explores new directions in which our approaches appear to have significant merit; and (iii) each aspect of the proposed program contains both fundamental research in mathematical sciences *and* important applications of direct relevance to Air Force missions. In particular, our research is directly relevant to problems including automatic target recognition based on synthetic aperture radar (SAR) and laser radar imagery; wide-area surveillance and information preparation of the battlefield (as envisioned, for example, in the "Targets under Trees" initiative formulated at the request of the Air Force Chief of Staff); global awareness and higher-level fusion for situational assessment; and fusion of multiple heterogeneous sensors as required to realize the vision for Predictive Battlespace Awareness and "Cursors on Target" concepts defined by the CSAF and recently examined in detail by the USAF Scientific Advisory Board. In all of these areas we have direct and strong contacts and interactions with AFRL staff and with industry involved in Air Force programs.

The principal investigator for this effort is Professor Alan S. Willsky. Prof. Willsky is assisted in the conduct of this research by Dr. John Fisher, research scientist in Prof. Willsky's group, by Dr. Mujdat Cetin, postdoctoral researcher in Prof. Willsky's group and by several graduate research assistants as well as additional thesis students not requiring stipend or tuition support from this grant. In the next section we describe our research accomplishments; in Section III we indicate the individuals involved in this effort; in Section IV we list the publications supported by this effort; and in Section V we discuss interactions and transitions.

II. Accomplishments

In this section we briefly describe the research accomplishments we have achieved with support provided by this grant. We limit ourselves here to a succinct summary and refer to the publications listed at the end of this report for detailed developments. However, we do note here that our work continues to have significant impact, both in terms of DoD-related activities and transitions in progress (Section V) and in terms of recognition from the research community (including the upcoming (Sept. 2003) plenary lecture to be delivered by Prof. Willsky at the IEEE Workshop on Statistical Signal Processing).

2.1 Multiresolution, Hierarchical, and Relational Modeling

The research described in this section is developed in great detail in a number of papers and reports [1,4,5,13,19-21,23-26,32-35, 47, 50-51, 55, 58-62, 64-66, 69, 71-72, 74, 77, 82, 85-87, 92-94]. The overall objective of this portion of our research is the development of methods for constructing stochastic models for phenomena that vary over space, time, and hierarchy and that possess structure which can be exploited to construct efficient and scaleable algorithms for statistical inference (the subject of subsequent sections of this report).

a) We have continued our research on construction of statistical models on multiresolution trees. Our most recent results involve a new and much tighter characterization of the conditional independencies that must hold among the values of a stochastic process defined on such a tree so that that process is Markov (more generally we develop conditions for Markovianity when we wish to match the distribution of the process values at a subset of the nodes of the tree). This new characterization leads directly to new algorithms for construction of exact and approximate multiresolution models starting either from the covariance specification of the "target" process (or more precisely the values of the process on the set of "target" nodes whose joint distribution we wish to model accurately) or directly from data.
b) We are also continuing our work on building models for certain types of non-chordal graphs with loops (i.e., graphs for which there is not necessarily a simple aggregation of nodes to produce trees). The motivation for this work comes from large-scale remote sensing problems such as arise in oceanographic data assimilation, in which we would expect to have both fine-scale covariance information locally but coarser-scale covariance information over larger areas—e.g., typical specifications of ocean statistics will specify covariances of processes at different resolutions, corresponding to specifying the covariance between spatial averages of the field. Such specifications lead to non-chordal graphs in which the coarser-scale variables whose correlations are known reside at coarser scales in a multiresolution graph. We are currently exploring application and extension of some recent results on non-chordal covariance extension and semidefinite programming to solve problems of this type.

c) A broad area for the extension of our multiresolution methodologies is to non-Gaussian and nonlinear models on both trees and on graphs with loops. Our most recent work in this area, which represents a new direction for us, is the use of nonparametric density estimation techniques to compute estimates of distributions at individual nodes and joint distributions between pairs of nodes. See the discussion in the next section for more on this approach, which simultaneously solves problems in modeling and in fusion.

d) We have continued our research on a new approximate MR modeling framework, which we refer to as ***Recursive Cavity Modeling*** that works directly with the *inverse* of the covariance of the process to be modeled. In particular, for an NxN covariance, if we reconstruct a graph with nodes $\{1,\ldots,N\}$ and an edge$\{i,j\}$if the ijth element of the *inverse* of the covariance matrix is *nonzero,* then the process is Markov with respect to this graph. An important property of such a model is that, conditioned on the values of the process on any *separator set* of nodes that partitions the graph into two or more disconnected components, the sets of values of the process on these disconnected components are mutually independent. This leads to a general methodology for constructing multiresolution models corresponding to a multiresolution sequence of nested partitions of this type, with very fine partitions at finer scales and coarser partitions at coarser scales. The problem with this method is that the dimensionality of the variables that form the state at any node of such a model is proportional to the number of nodes in the separator set corresponding to that node, and at coarser scales in the model, that dimensionality can be extremely large. Thus direct specification, manipulation, and storage of the covariance of such a state is prohibitively complex. However, while it is generally the case that the inverse of these state covariances are full, for many problems they are well approximated by sparse matrices, corresponding to Markov models for each of these separator sets. Our approach involves developing methods for the direct propagation of these sparse approximate models, using the same two-sweep (fine-to-coarse, coarse-to-fine) algorithmic structure as with our other multiresolution algorithms. Since each of these boundaries encloses a region of the graph, we refer to these as *cavity models.* During this past year we have developed a very general framework that makes extensive use of information-geometry to develop iterative algorithms for optimal recursive cavity modeling applicable to general graphical models—i.e., not limited to Gaussian processes and, in fact, just as applicable to nonlinear, discrete, and hybrid continuous/discrete data. We are currently working on a first paper developing and applying the method for the Gaussian processes.

e) As discussed in the next subsection, we have had great success with the development of a new class of algorithms that we refer to as ***Embedded Tree (ET) Algorithms.*** The success of these algorithms has motivated the initiation of research on building multiresolution models on structures for which ET algorithms offer superior performance. Among these structures are models on what we refer to as "near-tree" structures, i.e., multiresolution trees augmented with a comparatively small number of "cross-links" between nodes that are close spatially but much more distant as measured along the graph prior to augmentation. These models allow us to overcome one of the limitations of pure tree models, namely the potential for errors and artifacts across such major tree boundaries, while the ET algorithm allows us to exploit the efficiency of tree-based models. We have now demonstrated that such models, with the introduction of very few edges, can lead to models with dramatically superior approximation power (and with little loss in the efficiency of associated estimation algorithms). We are currently working on efficient methods for building such models by adding edges successively, in part borrowing from the same set of tools used in our work on recursive cavity modeling.

2.2 Sensor Fusion Algorithms over Space, Time, and Hierarchy

The research described in this section deals with efficient algorithms for large-scale optimal estimation and is reported in detail in [3,6,20,23,26,30-35, 47, 50-51, 55, 58-62, 64-66, 69, 71-72, 74, 77, 82, 85-87, 92-94]. The general objective for this part of our research is to investigate stochastic models with structure that can be exploited in order to develop optimal or near-optimal algorithms that are scaleable to the large-scale problems encountered in image analysis, sensor fusion, and higher-level fusion. Our research here involves the development of algorithms that parallel the modeling efforts described in the preceding subsection as well as several other initiatives involving graphical modeling concepts:

a) As mentioned in the preceding subsection, we also have had considerable success in our development of *Embedded Tree (ET) Algorithms*. The objective of this work is to exploit our powerful algorithms for estimation and fusion on trees in order to develop more global algorithms than the predominant algorithmic concept in the field of graphical models, namely Pearl's algorithm, which is optimal for trees but provably suboptimal for graphs with cycles (in particular for linear-Gaussian problems, Pearl's algorithm, when it converges, gives the correct estimates but incorrect error covariances). In our algorithmic framework, we view the edge set of a graph with loops as the union of edge sets of *spanning trees* each of which comes from discarding a subset of the edges of the original graph. Using this structure we can directly define iterative algorithm in which we perform tree-based estimation using each of these embedded tree models in succession. We have shown that such algorithms, when they converge, both yield the optimal estimates *and* the correct error covariances. Furthermore, experimental results demonstrate that these algorithms converge in many more situations than Pearl's algorithm. Indeed, by exploring ties of these methods to work in numerical linear algebra for the solution of large linear systems, we have both developed new algorithms for that community plus borrowed some ideas to develop even more powerful algorithms for graphical model estimation that result from using our embedded tree algorithm as a preconditioner for conjugate gradient algorithms. We have demonstrated the power of these methods for large-scale multisensor fusion problems (involving thousands of sensing nodes) and in estimation of random fields and processes.

b) As was also discussed in the preceding section, we have been working on the development of a methodology for *Recursive Cavity Modeling and Estimation*. In particular, the methodology for constructing these models directly leads to efficient two-sweep algorithms for estimation and fusion, propagating information around the boundary of each cavity and then propagating first outward as cavities grow and are merged and inward. We have demonstrated the power of these algorithms for a variety of large Gauss-Markov random fields, and a paper on these results is in progress. Moreover, as mentioned in the preceding section, we have extended the concept of recursive cavity modeling to general, non-Gaussian graphical models, using powerful ideas and results from information geometry, and we are now beginning to investigate the utility of this extension to a variety of estimation and distributed fusion problems.

c) We have continued our work on several different algorithms and problems related to what we have called *tree-reparametrization (TRP) algorithms*. The work reported previously—and on which we continue to work as well—focuses on the computation of marginal distributions at each node in a graphical model—the same problem for which Pearl's belief propagation algorithm (alternately known as the sum-product algorithm) represents an approximate solution. Each iteration of a TRP algorithm involves operations over a tree embedded in the graph. The critical idea here is the recognition that optimal algorithms on trees correspond to performing a *refactorization* of the probability distribution for the entire process, one that explicitly exposes the marginal distributions for each node in the graph. TRP algorithms iterative perform this refactorization over a set of trees. In our work we have demonstrated that this algorithm has better convergence properties than Pearl's algorithm and have also developed important theoretical results on the characterization of fixed points of these iterations, on necessary conditions for convergence using a pair of spanning trees, and on bounds on the errors in these algorithms. The latter results involve careful use of concepts in convex duality to obtain methods for optimizing our bounds over all embedded trees in a graph. Since there are generally many embedded trees, performing this optimization directly is completely intractable. However, the use of a dual formulation reduces this to a remarkably simple optimization problem. More recently we have focused on another problem of great practical importance—e.g., in multisensor data association and in coding applications—namely that of computing the overall MAP estimate, i.e., the peak of the overall joint distribution for all variables on the entire graph. If the graph is a tree—i.e., contains no cycles—this computation can be performed very efficiently either in a two-sweep fashion, generalizing the dynamic programming structure of the celebrated Viterbi algorithm or in a local message-passing algorithm, analogous to the sum-product algorithm and often referred to as the *max-product algorithm*. However, if the graph of interest contains loops, performing MAP estimation is, in general NP-Hard, and the application of the max-product algorithm to such graphs not only may not converge but also leads to suboptimal solutions when convergence does occur. In our work we have developed counterparts of our TRP algorithms that are aimed at the MAP problem instead. In part this work allows us to develop both algorithms that converge more frequently than standard max-product algorithms and also analyses of the properties of fixed points. In addition, by adapting our ideas on using multiple trees, we have been able to develop a *tree-reweighting* algorithm that is guaranteed to converge to the true MAP estimate under fairly mild conditions. Indeed these conditions in essence define the space of problems in which distributed message-passing algorithms such as max-product or our new ones *should* be applied (as when these conditions are violated, MAP estimation cannot be performed solely via local computations).

d) One of the motivations for the work just described on MAP estimation is the development of efficient algorithms for multisensor, multitarget data association, a notoriously complex problem. We have now demonstrated that our new approach to max-product and tree-reweighting algorithms can yield remarkably efficient solutions to optimal data association problems that have heretofore been considered too complex for practical solution (hence requiring the use of heuristics to obtain tractable, but suboptimal, solutions). This work is now focused on several extensions, including to the examination of how convergence varies as a function of the set of trees used (ranging from "trees" consisting of single pairs of nodes as in the max-product algorithm to full spanning trees), number of iterations, and the difficulty of the association problem as measured in terms of the level of contention (multiple measurements contending for association with particular targets and multiple targets contending for association with particular measurements).

e) As mentioned in the previous section, we are developing new approaches to inference for graphical models that involve non-Gaussian densities—problems of particular importance for various sensing modalities that provide measurements of either bearing or range. These methods, which involve the use of methods for nonparametric density estimation (for which reason we refer to them as *Nonparametric Belief Propagation* algorithms), can be viewed as extensions of concepts of particle filtering to inference on graphs—this extension is highly nontrivial, especially for graphs with loops, as the iterative computations and generation of messages of belief propagation require new ideas for generating "particles" to replace those messages. In addition to developing the basic methodology, we are also exploring applications in both computer vision and in fusion for sensor networks.

f) Finally, motivated by problems of fusion for sensor networks, we have recently initiated a new look at message-passing algorithms for inference on graphs, namely a look that brings in both the cost of communication as well as ideas from other disciplines, most notably decentralized estimation and hypothesis testing. Our intention here is to develop new approaches that synthesize concepts from this disparate disciplines. Among the problems being investigated are (1) including additional protocol bits in messages in belief propagation or TRP algorithms that provide information on the path that each message has taken and hence allow receiving sensor nodes to account for the fact that information embedded in these messages may be correlated (because of loops in the network graph); (2) examining problems of finite-bit messages in belief propagation, generalizing ideas of decentralized detection to loopy graphs; and (3) building on results in decentralized detection to develop algorithms for network self-organization, including determining how to distribute estimation responsibility to nodes in a network (i.e., which node estimates which variables).

2.3 Statistical Modeling and Estimation of Shape with Applications in Object Extraction and Recognition

The general objective of this part of our research is the development of statistically robust methods for segmentation and shape estimation with applications ranging from wide-area mapping to object recognition, and the results of our efforts in this area are developed in detail in publications [10-12,22,36-41, 46, 54, 57, 74, 78-84, 88, 91, 102-103]. Essentially all of our recent work in this area has focused on so-called curve evolution methods and, in particular, on developing statistically-based curve evolution algorithms. Our earlier work—e.g., on developing curve evolution algorithms for the image processing problem of Mumford and Shah—has received considerable recognition, motivating the work we now describe:

a) In recent research we have extended our curve evolution ideas to allow us to include blurring—i.e., to consider image deblurring as well as denoising and segmentation—as part of a single, unified formulation. Interestingly, in this case the PDE's inside and outside the curve are now coupled, thanks to the blurring of the image data, and there are a number of interesting and important theoretical and algorithmic issues to which this gives rise and which are currently under investigation.
b) One of the major areas of our current and future research in this area is that of incorporating prior information about shape into curve evolutions. This is particularly important for problems in which image SNR is low or in which the objects of interest are partially occluded. Major issues here include the development of methods for constructing prior probability distributions on shapes from examples and the incorporation of these priors into curve evoloution formalisms. In our initial work in this area we used a set of training examples to construct a set of "eigenshapes," which then are used to provide a *linear* parameterization of a set of shapes, where the parameters of that linear parametrization is then estimated as part of the curve evolution process. Results on both military and medical images in both 2-D and 3-D have demonstrated that this methodology has a great deal of promise. A paper on this topic received the Best Paper Award at IEEE CVPR, and recently we have extended these results to problems in which there are multiple objects to be segmented simultaneously. A key idea here is that by doing this, we can use knowledge of the relative locations and shapes of a set of objects to allow

us to couple the estimation of each. For example, if one object is particularly easy to segment in an image, the availability of a joint model allows us to use this segmentation to guide the segmentation of other objects that may be more difficult to segment on their own.

c) We have also continued our work on an approach that blends both curve evolution methods as described in this subsection and the nonparametric methods for statistical learning discussed in the next. In particular, we have developed a method for image segmentation that assumes only that the image under question consists of two types of regions, each of which is characterized by a different but completely unknown probability distribution. The approach we have taken is that of attempting to estimate these probability distributions *at the same time as we are performing segmentation.* The approach which (for large images) is asymptotically equivalent to full maximum likelihood segmentation, involves explicitly nonparametric estimation of the probability distributions given a current estimated segmentation together with a curve evolution that attempts to increase the Kullback-Leibler divergence between the estimated distributions. The curve evolution actually involves several other terms which account for the fact that we may be dealing with small images or, more importantly, with the detection of relatively small regions within an image. In this case, the curve evolution must account for the fact that evolving the curve will change the set of pixels considred to be within a given region which in turn will change the estimated probability distribution. An invited paper on this work will be presented at the upcoming ICIP conference.

d) Finally, we have recently initiated a new effort aimed at space-time tracking of curves or boundaries that evolve in time themselves. This is of particular importance in problems such as estimating local variations in meteorological conditions in, say, a battlefield environment (as envisioned in the so-called WeatherWeb concept). Our approach to this problem involves developing and exploiting models for the probabilistic evolution of such curves—in essence developing temporal Markov models for these curves. We are exploring several approaches to this problem, including one that blends the learning of linear parameterizations of curves as described in item "b" above with our methods for learning dynamic models in time, as described in the following section.

2.4 Blending Physics and Statistical Learning for Image Reconstruction, Feature Extraction, and Fusion

In this section we describe our research on marrying sensor physics with statistics and nonparametric statistical methods in order to develop robust methods for exploiting the information present in sensor data. The fundamental idea here is that a full, heavy use of fundamental physics (e.g., solving Maxwell's equations) is clearly inappropriate for sensor fusion since there are limitations in the "apertures" through which we view the phenomenon both from the input and output sides. In particular, the data that are typically available (e.g., to form a SAR image) are far too limited in extent and subject to too many sources of uncertainty and variability to warrant full solution of the inverse scattering problem in order to form an image. Fortunately, and complementary to the limitations in the observed data is the fact that the desired information we wish to extract from such sensor data--e.g., detections and classifications of objects--are far more limited than a complete inverse scattering solution. On the other hand, discarding all physics also is unwise, as the constraints implied by sensor physics can be used to reduce the apparent number of degrees of freedom in the data, thus enhancing the quality of any statistical analysis. The challenge is to determine the proper balance between physics/model-based methods and statistical/learning methods. This is a deep and enduring theme to which we believe we have made some contributions. Our work to date in this broad area is described in [2,7-9,14-18,27-29,42-45, 48-49, 52-53, 56, 63, 67-70, 73, 76, 83, 89, 90, 95-101, 104-108].

a) In this part of our research we have taken a deeper look at marrying SAR physics with nonparametric statistical learning methods for constructing probabilistic models for multiresolution imagery. In particular consider the formation of SAR imagery based on a given full aperture of data. If we use the entire aperture, we obtain imagery at the finest resolution resolvable using that data. However, to do this we in essence must assume that all scattering is isotropic, i.e., that the response from significant scatterers is constant across the entire aperture. For many important scattering mechanisms this is not the case at all, and this anisotropy is critical to distinguishing one scatterer type from another. Suppose then, that in addition to forming an image using the entire aperture, we also form three images each using half of the aperture: one image using the right half, one the left, and one using a centered half-aperture. If indeed there are anisotropic scatterers, we might expect that there would be differences in the responses in each of these half-apertures and hence in the images formed using them (note that these images would have pixel sizes twice as large as the ones in the finest scale imagery). Iterating this process, we can imagine forming a vector of images at each of a sequence of scales corresponding to progressively smaller subapertures. By looking across scale, then, we would expect not only to find statistical variability due to speckle but also any evidence of anisotropic scattering manifesting itself in statistically significant differences in pixel intensities in images formed using different subapertures. During the past year we have developed hybrid estimation algorithms based on these ideas. Our basic algorithm involves both the estimation of the level of anisotropy for each pixel as well an estimate of reflectivity consistent with the anisotropy estimate. Together these provide both sharpened estimates of reflectivity as well as augmented features (namely anisotropy designations) that should be useful for target recognition. One of the challenges in developing such an algorithm is that smaller subapertures do not simply measure information from the scatterer pixel of interest but also are corrupted by energy from neighboring scatterers. Thus, our hybrid estimation procedure for estimating anisotropy and reflectivity for a given pixel must deal with "nuisance" parameters corresponding to scattering from neighboring pixels. In our basic non-iterative algorithm this is accomplished independently at each pixel, in which effects of neighbors are estimated and removed. However, a more sophisticated approach would be to use an iterative procedure in which the actual estimates produced at neighboring pixels at each iteration were used to enhance the next iteration's estimate of each pixel. Such a method has been developed and promising, enhanced imaging results have been demonstrated in which spatially extended (and thus highly anisotropic) scatterers are identified and dealt with in a way that enhances the resulting image appearance.

b) A continuing and very active component of our research focuses on variational methods to produce enhanced images and reconstructions for SAR, ISAR, and more general array processing applications. In particular, by putting particular penalties (e.g., L_p, with $p < 1$) either on the reconstructed image or on the gradient of the reconstructed image, we have shown that we can produce remarkably sharp images of point scatterers or regions and can also correct for phase errors due to target motion—an extremely important problem in SAR imaging of moving targets or to other sources (including timing errors to array element location errors). Moreover, in contrast to many other superresolution methods (e.g., MUSIC, Capon's method), our method can resolve multiple scattering effects that are highly correlated—e.g., due to the presence of multipath effects. In our most recent efforts we have developed new variational approaches for array processing that work well for broadband sources and, in particular, for sources that generate multiple harmonics (e.g., as are present in any motor or machinery).

c) We have also continued our work on exploiting ideas from nonparametric statistics, information theory, and machine learning to develop algorithms for a number of different problems in signal analysis and fusion. One such application is the construction of dynamic models from complex signals in an unsupervised learning context. The principle we have adopted in this and in our other work in this area is that of maximizing mutual information. In particular, in this context, the objective is to identify functionals of the past of a signal that have maximal mutual information with the next value of the signal. In the process of performing that optimization using nonparametric statistical methods, we also build a model for the transition probability for the process, i.e., the conditional pdf for the next value of the signal given these maximally informative functionals of the past. This pdf, then, serves as a *dynamic model* of the phenomenon which can be used for signal prediction, simulation, discrimination, and estimation. To illustrate the power of this method, we have applied it to a variety of signals including the 2-D trajectory corresponding to signatures, which we have then used to detect forgeries. We are also investigating the use of this methodology both for the development of statistical models for dynamically evolving curves (as described in the preceding section) and for the problem of separating multiple unknown sources from multiple sensor outputs.

d) A second context in which we are developing nonparametric/information-theoretic methods is that of the fusion of signals of very different modalities. In particular, our initial work in this area has focused on the fusion of video imagery and acoustic signals. The challenge in this case is to determine what actions in the video sequence are responsible for what components in the observed acoustic signals. The potential applications of this for multisensor fusion and for enhanced source separation (e.g., using video to enhance acoustic signal separation or using audio to help identify significant objects and activities in image sequences) are myriad. The results on preliminary imagery are striking in their ability to localize sources of sound and to use video to guide the separation of acoustic signals. In addition, we are actively involved in developing analogous methods to provide nonparametric methods for multisensor data association. For example, in complex environments it may not be possible to combine data from distributed sensors in straightforward coherent fashion, e.g., due to variabilities in received signatures from different viewing angles or to dispersive or nonlinear effects that disrupt signal coherency. We have now written a first paper on this problem and are working on a general approach that overcomes the computational complexities that arise in large-scale data association problems.

III. Personnel

The following is a list of individuals who have worked on research supported in whole or in part by the Air Force Office of Scientific Research under Grant F49620-00-1-0362:

Prof. Alan S. Willsky, Edwin Sibley Webster Professor of Electrical Engineering, MIT
Dr. John Fisher, Research Scientist, MIT Lab. for Information and Decision Systems
Dr. Mujdat Cetin, Research Scientist, MIT Lab. For Information and Decision Systems
Dr. Michael Schneider, recent Ph.D., postdoctoral researcher
Dr. Austin Frakt, recent Ph.D.
Dr. Terrence Ho, recent Ph.D.
Dr. Andy Tsai, recent Ph.D.
Dr. Andrew Kim, recent Ph.D.
Dr. John Richards, recent Ph.D.
Dr. Martin Wainwright, recent Ph.D., postdoctoral researcher
Dr. Ron Dror, recent Ph.D.
Mr. Dewey Tucker, graduate student
Mr. Erik Sudderth, graduate student
Mr. Jason Johnson, graduate student
Mr. Junmo Kim, graduate student
Mr. Alex Ihler, graduate student
Mr. Ayres Fan, graduate student
Mr. Lei Chen, graduate student
Mr. Dmitry Malioutov, graduate student
Mr. Walter Sun, graduate student
Mr. O. Patrick Kreidl, graduate student

IV. Publications

The publications listed below represent papers, reports, and theses supported in whole or in part by the Air Force Office of Scientific Research under Grant F49620-00-1-0362:

[1] W.W Irving and A.S. Willsky, " A Canonical Correlations Approach to Multiscale Stochastic Realization," *IEEE Trans. on Automatic Control*, Vol. 46, No. 10, Oct. 2001, pp. 1514-1528.

[2] J.W. Fisher, A. Tsai, C. Wible, J. Kim, A.S. Willsky, and W.M. Wells, "Activation Detection in fMRI Using Information Theory and Markov Random Fields," in preparation.

[3] M. Schneider, "Computationally Efficient Random Field Estimation Algorithms Using Conjugate Gradient Algorithms," Ph.D. thesis, Jan. 2001.

[4] D. Tucker, "Learning Algorithms for Multiresolution Pyramidal Models," Ph.D. thesis, to be completed, Jan. 2004.

[5] A.B. Frakt and A.S. Willsky, "A Scale-Recursive Method for Constructing Multiscale Stochastic Models," *Multidimensional Systems and Signal Processing,* Vol. 12, 2000, pp. 109-142.

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V. INTERACTIONS/TRANSITIONS

In this section we summarize the various interactions and transitions associated with research supported by AFOSR Grant F49620-00-0362.

Participation/Presentation at Meetings

In addition to presentations at professional conferences, we have been involved in the following other meetings:

(1) Prof. Willsky participated in the joint DUST/DARPA workshop on future directions for ATR, held in July 2001. This meeting, attended by invitation only primarily by government and industry, had as its aim the identification of the next generation of directions for basic and applied research and development in ATR, with the objective of providing DUST and DARPA with the seeds for future initiatives in this area.
(2) For the second consecutive year Dr. Mujdat Cetin was asked by conference organizer, Mr. Edmund Zelnio, to participate in a panel dealing with advanced radar imaging methods, held as part of the SPIE Aerosense Symposium.
(3) Prof. Willsky was invited to participate in the AFOSR-AFRL/IF Strategic Planning Workshop, held at Dartmouth College, August 2002. The intent of this meeting was to define strategic directions for research and development in the information sciences, broadly defined. Prof. Willsky will likely chair the next of these workshops, tentatively planned for 2004.
(4) Dr. Martin Wainwright was invited by Dr. Wendy Martinez of ONR to present some of his research, supported by this AFOSR grant, at the 2002 Army Statistics Meeting.
(5) Dr. John Fisher was asked to give an invited presentation at Lincoln Laboratory on his work on information-theoretic methods for multisensor fusion. This, together with other interactions led by Dr. Cetin, have led to increasing collaborations and interactions between our research team and Lincoln researchers and programs.

Consultative and Advisory Functions

We continue to be actively engaged in a number of activities relevant to the research being performed under our AFOSR grant:

(1) Prof. Willsky has regularly acted as a consultant to Alphatech, Inc. in a number of research projects including ones that represent direct transitions of the technology being developed under our AFOSR Grant. These have, in fact, accelerated during this past year, as we are actively involved in several transitions of our work.

(2) Prof. Willsky recently completed his 4-year term on the Air Force Scientific Advisory Board. During his term:

a. He twice served as a panel member for the AF/SAB S&T Review of AFRL/SN and the relevant parts of AFOSR supporting SN.
b. He twice served as a panel member for the AF/SAB S&T Review of AFRL/IF and the relevant parts of AFOSR supporting IF.
   i. He participated in three AF/SAB summer studies. These each involved extensive visits to AF and other service organizations, and the writing of portions of the AF/SAB reports for the studies briefed to the Secretary of the Air Force and the AF Chief of Staff. Most recently, Prof. Willsky participated on the Information Integration and Management Panel for the AF/SAB study on Predictive Battlespace Awareness, commissioned directly by CSAF. Prof. Willsky's specific role in this study was to examine and make recommendations on S&T needs for fusion to support Predictive Battlespace Awareness (report is written and is currently under review by the AF/SAB prior to release).
c. In addition, because of his recognized expertise in information integration and fusion, Prof. Willsky was asked to help support one of this current year's studies—on Machine-to-machine ISR integration.
d. Finally, on completing his tenure on the AF/SAB, Prof. Willsky received an Award for Meritorious Civilian Service.

(3) At the request of Mr. E. Zelnio of AFRL/SN, Prof. Willsky participated as a member of an ad-hoc panel helping Mr. Zelnio and AFRL with its plan for technology insertion to meet both short- and intermediate-term objectives related to the "Tanks under Trees" initiative requested by the Air Force Chief of Staff in response to needs identified in Kosovo operations.

(4) Through contacts made on the AF/SAB, Prof. Willsky has been asked to act as an informal consultant to staff of the National Reconnaissance Office. In particular, Prof. Willsky has been asked to provide advice on future directions for information technology and fusion.

Transitions

The following are the transitions of our research that are taking place:

(1) Our multiresolution SAR discrimination algorithms, most recently for the classification of nonisotropic scattering behavior, are being transitioned to Alphatech for inclusion in advanced model-based ATR algorithms. The point of contact on this is Dr. Gil Ettinger.

(2) Our efficient methodology for multiresolution mapping and data fusion have been transitioned to Alphatech as part of an SBIR program, through NIMA, on fusion of multiresolution and multipass data to produce high-fidelity terrain maps. Alphatech is currently engaged in planning for a subsequent use of our

methods for a program through TEC (the Army Topographic Engineering Center). The points of contact are Mr. Thomas Allen and Mr. Laughton Stanley.

(3) Our work on curve evolution methods are being transitioned to Alphatech for use both in ATR applications and for NIH-sponsored R&D on brain image segmentation for the temporal tracking of multiple sclerosis lesions and for MRI segmentation of the prostate for in order to guide cancer treatment. The points of contact for this work are Dr. Gil Ettinger, Dr. Joel Douglas, and Dr. Matt Antone.

(4) Transition of our multiresolution estimation and uncertainty characterization algorithms to Alphatech for a DARPA program on uncertainty characterization in littoral waters. The point of contact for this work is Dr. Eugene Lavely.

(5) Transition of our graphical estimation methods to Alphatech for several programs, including road network estimation for DARPA's Dynamic Database (DDB) Program and to several higher-level fusion algorithms sponsored by DARPA and AFRL/IF. The points of contact for this work are Dr. Joel Douglas, Dr. Mark Luettgen, and Dr. Eric Jones.

(6) Transition of our nonparametric learning algorithms to Alphatech for the problem of HRR (high-range resolution radar) feature-aided tracking (FAT), in which the challenge is characterizing variability in HRR profiles and predicting what such profiles will look like from new viewing geometries to facilitate fusion in a FAT system. The points of contact for this work are Mr. Brian Hodges and Mr. Herb Landau.

(7) Transition of our new algorithms for graphical optimization to several Alphatech programs, including new methods for data association for multitarget tracking to be used in a number of programs including the DARPA AMSTE program being run by AFRL/IF and DARPA's DTT program (points of contact Dr. Robert Washburn and Dr. Mark Luettgen) and to the extraction of "links" in complex, heterogeneous data and construction of models of behavior from huge data repositories under DARPA's EELD (Evidence Extraction and Link Discovery) Program (points of contact Dr. Eric Jones and Dr. Robert Washburn).

(8) Transition of our information-theoretic methods for signal fusion to DARPA's ISP program (points of contact Dr. Mark Luettgen and Dr. Michael Schneider).